

The BOUT Project; Validation and Benchmark of BOUT Code and Experimental Diagnostic Tools for Fusion Boundary Turbulence

X. Q. Xu

This article was submitted to
Chinese Youth Workshop on Plasma Physics and Fusion Research
Hefei, China
August 20-25, 2001

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

August 9, 2001

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (423) 576-8401
<http://apollo.osti.gov/bridge/>

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161
<http://www.ntis.gov/>

OR

Lawrence Livermore National Laboratory
Technical Information Department's Digital Library
<http://www.llnl.gov/tid/Library.html>

August 9, 2001

The BOUT Project; Validation and Benchmark of BOUT Code and Experimental Diagnostic Tools for Fusion Boundary Turbulence*

X. Q. Xu

Lawrence Livermore National Laboratory

Livermore, CA 94551

United States of America

A boundary plasma turbulence code BOUT is presented. The preliminary encouraging results have been obtained when comparing with probe measurements for a typical Ohmic discharge in CT-7 tokamak. The validation and benchmark of BOUT code and experimental diagnostic tools for fusion boundary plasma turbulence is proposed.

*Work performed under the auspices of the U. S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

I. INTRODUCTION

The performance of tokamaks and other toroidal magnetic devices depends crucially on the dynamics of the boundary region, i.e., the transition region from the hot core plasma through the separatrix to the material surface of the first wall. Plasma turbulence, and the resulting anomalous cross-field plasma transport, are crucial physics processes in the boundary region, affecting both core plasma confinement and plasma-wall interactions. Reduction of anomalous plasma transport at the boundary, associated with the transition to the H-mode operating regime, leads to sharp pedestal-like structures in the temperature and density profiles. The large anomalous transport to wall has recently been argued necessary to explain the experimental measurements for main chamber recycling and for the scrape-off-layer (SOL) and/or core plasma particle balance.

The goal of the BOUT project is the development and deployment of a user-friendly, state-of-art, nonlinear fluid turbulence capability for the analysis of boundary turbulence in a general geometry on a routine basis. BOUT models the 3D electromagnetic boundary plasma turbulence that spans the separatrix using a set of fluid moment equations with the neoclassical closures for plasma vorticity, density, ion and electron temperature and parallel momentum, and with proper sheath boundary conditions in the SOL.^{1,2} The BOUT code solves these equations in a 3-D toroidal segment, including the region somewhat inside the separatrix and extending into the SOL; the private flux region is also included. With poloidal flux, ψ , normalized to unity on the separatrix, we typically take the inner simulation boundary condition to be $\psi_c=0.9$ and the outer boundary at $\psi_w=1.1$. The boundary conditions are homogeneous Normann at $\psi = \psi_c$ and at $\psi = \psi_w$, sheath boundaries in the SOL and the private flux regions, periodic in poloidal direction in “edge” (inside of separatrix), and periodic in toroidal direction. A finite difference method is used, and the resulting difference equations are solved with a fully implicit, parallelized, Newton-Krylov solver PVODE/PVODE. In order to investigate boundary turbulence, BOUT is able to couple to the edge plasma transport code UEDGE, and MHD equilibrium code EFIT to get the realistic X-point divertor magnetic geometry and plasma profiles.

BOUT contains much of the relevant physics for the pedestal barrier problem for the experimentally relevant X-point divertor geometry. Encouraging results have been obtained when using measured plasma profiles in current generations of major US fusion devices such as DIII-D, C-Mod and NSTX. The resistive X-point mode has been identified in a X-point divertor geometry.^{3,4} Comparison of the shifted-circle vs. X-point geometry show the different dominant modes and turbulence fluctuation levels.² The poloidal fluctuation phase velocity shows experimentally observed structure across the separatrix in many fusion devices.⁵ The fluctuation phase velocity is larger than ExB velocity. The Quasi-Coherent mode is believed to be responsible for the high energy confinement (H-mode), yet acceptably low particle (impurity) confinement in the Alcator C-Mod high density plasma regime. The experimentally measured dispersion and mode stability is in good agreement with the resistive ballooning X-point mode predicted by the BOUT code.⁶ A strong poloidal asymmetry of particle flux in the proximity of the separatrix may explain the paradox of the JET probe measurement of the particle flux when comparisons of the limiter vs. divertor experiments had been made.² Our L-H transition with simple sources added shows transitions with resistive X-point modes dominating L-mode. The levels of turbulence are similar to experimental measurements.⁵

There exist many experimental turbulence measurements in the pedestal region and in the SOL. The common measurements are the electrostatic probes, reflectometry, and phase contrast imaging (PCI), Beam Emission Spectroscopy (BES), and Gas Puff Imaging (GPI). It is the time to obtain coherent understanding of the boundary turbulence dynamics and benchmark BOUT results with the experimental measurements. The diagnostic tools typically limit either to the local measurements in space or to particular turbulence quantities with certain work assumptions. With the well bench-marked code at the location to the particular measurement, or to particular turbulence variables, the BOUT is able to validate the diagnostic tool, patch the experimental measurements together and yields global understanding of the boundary turbulence dynamics. The special effort will boost boundary turbulence modeling to obtain a realistic simulation tool for experimental data analysis on a routine basis. It will stimulate theoreticians, modelers, experimentalists, and computer scientists to work together and to build solid understanding of boundary turbulence based on the common ground.

II. Preliminary BOUT simulations of HT-7 tokamak

As an example here, the BOUT simulations are carried out using HT-7 tokamak boundary plasma parameters: $R_0=122\text{cm}$, $a=27.5\text{cm}$, $q(a)=2$, $\hat{s}=1$. The radial equilibrium profiles of plasma density $n_e(r)$ and $T_e(r)$ are taken from the measurements of the fast reciprocating Langmuir probe.⁷ We use the hyper-tanh fit with the density scale length $L_n(a)=1.85\text{cm}$ and electron temperature scale length $L_{T_e}(a)=3.1\text{cm}$. The electron temperature and density at the separatrix are $T_e(a) = 19\text{eV}$ and $n_e(a) = 1.8 \times 10^{12}/\text{cm}^3$ respectively. No experimental measurements of either the ion temperature or the radial electric field are available. Given the high collisionality it is reasonable to assume $T_i = T_e$; while the radial electric field is obtained from the nonlinear simulations themselves. The time history of the density fluctuation and electric potential are shown in Fig. 1. The simulation starts from small fluctuations of random noise, then it undergoes the linear growing phase. At $\omega_{ci}t \sim 500$, the unstable modes inside the separatrix enter into a nonlinear phase. After a period of adjustment, the turbulence-generated electric potential reaches its peak amplitude inside the separatrix; the fluctuating density and turbulent particle flux are significantly suppressed there after $\omega_{ci}t \sim 10000$. However, the fluctuating density remains large in the SOL outside separatrix.

The time history of the radial profile of the turbulence-generated particle flux is shown in Fig. 2(a). Similarly as the fluctuating density, after a period of adjustment, the turbulence-generated shear flow significantly suppressed the particle flux inside the separatrix after $\omega_{ci}t \sim 10000$. However, the fluctuating particle flux outside separatrix remains large and bursting. Fig. 2(b) shows the radial profile of the root-mean-square (rms) of particle flux. The peak amplitude is $\Gamma \sim 3 \times 10^{19}/\text{m}^2/\text{s}$, which is consistent with the probe measurements.⁷ The radial profiles of the rms density, electric potential, electron and ion temperature are given in Fig. 3. They are again consistent with the probe measurements. The radial profiles of turbulence-generated electric field E_r is plotted in Fig. 4. Though the radial electric field E_r is dominated by the sheath potential in the SOL, there is still some modification by the turbulence, especially in the proximity of the separatrix.

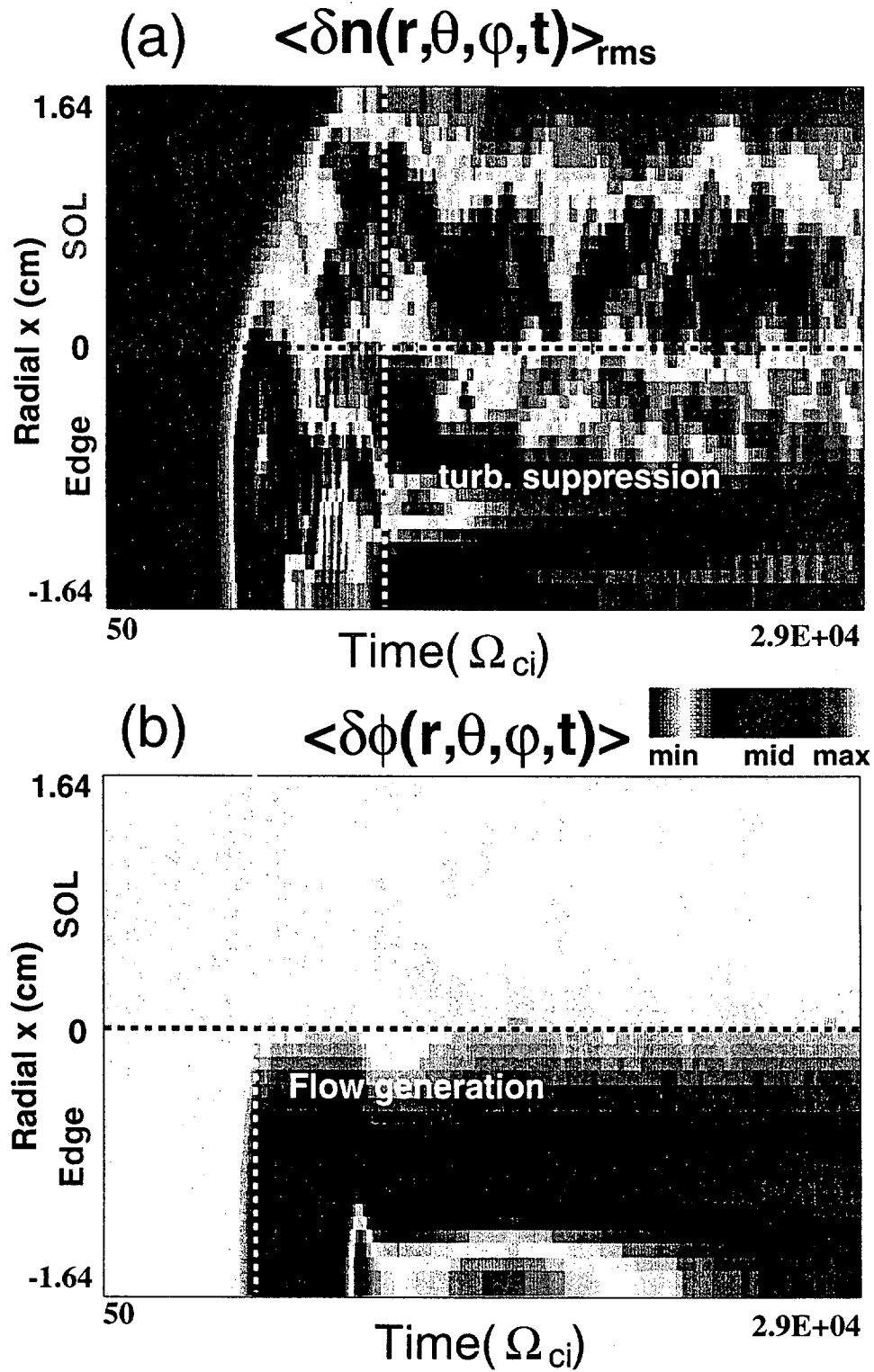


Figure 1: (a) The time history of rms amplitude of fluctuating density; (b) The flux surface averaged electric potential.

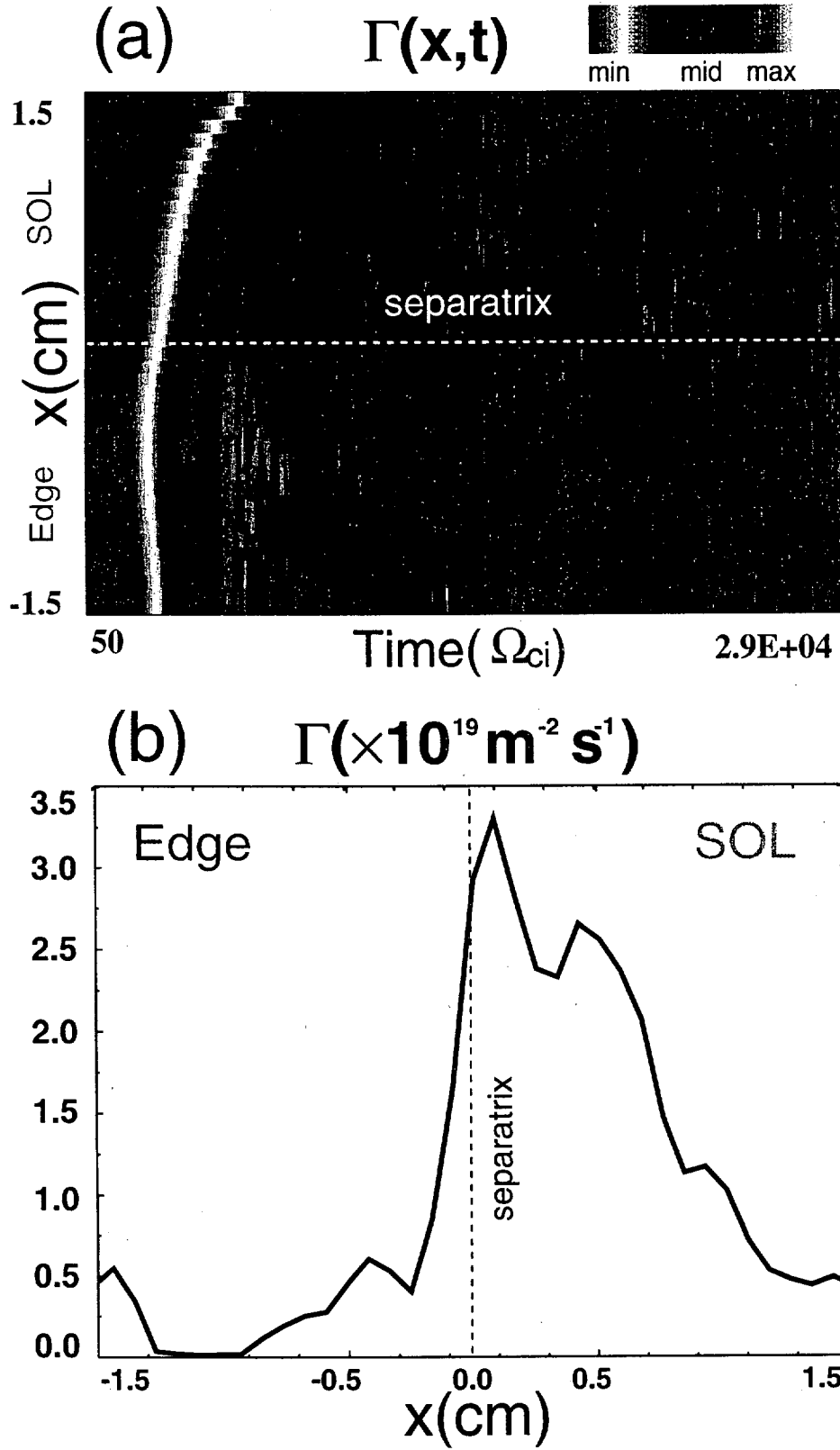


Figure 2: (a) The time history of turbulent particle flux; (b) The flux surface and time averaged turbulent particle flux.

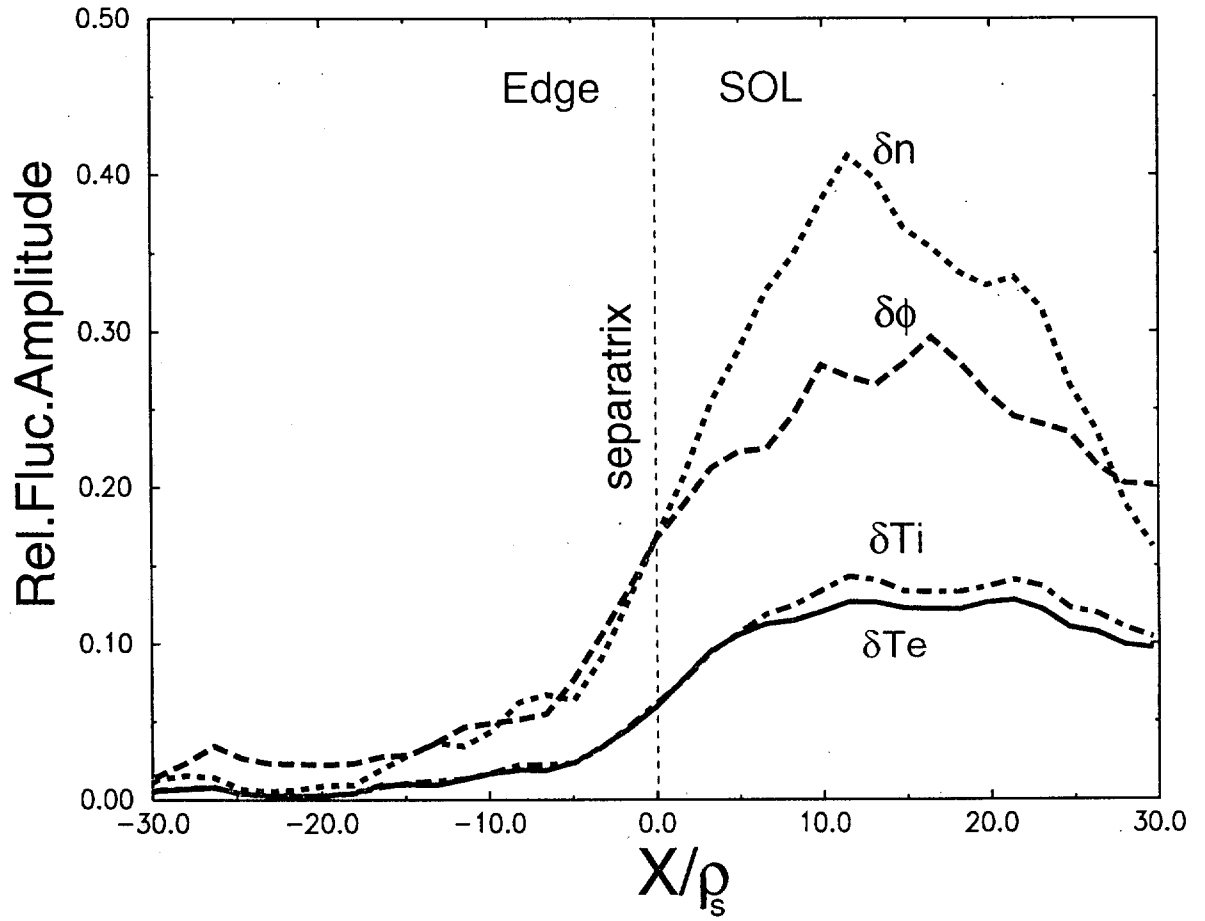


Figure 3: The radial profiles of the rms fluctuating density, potential, electron and ion temperature.

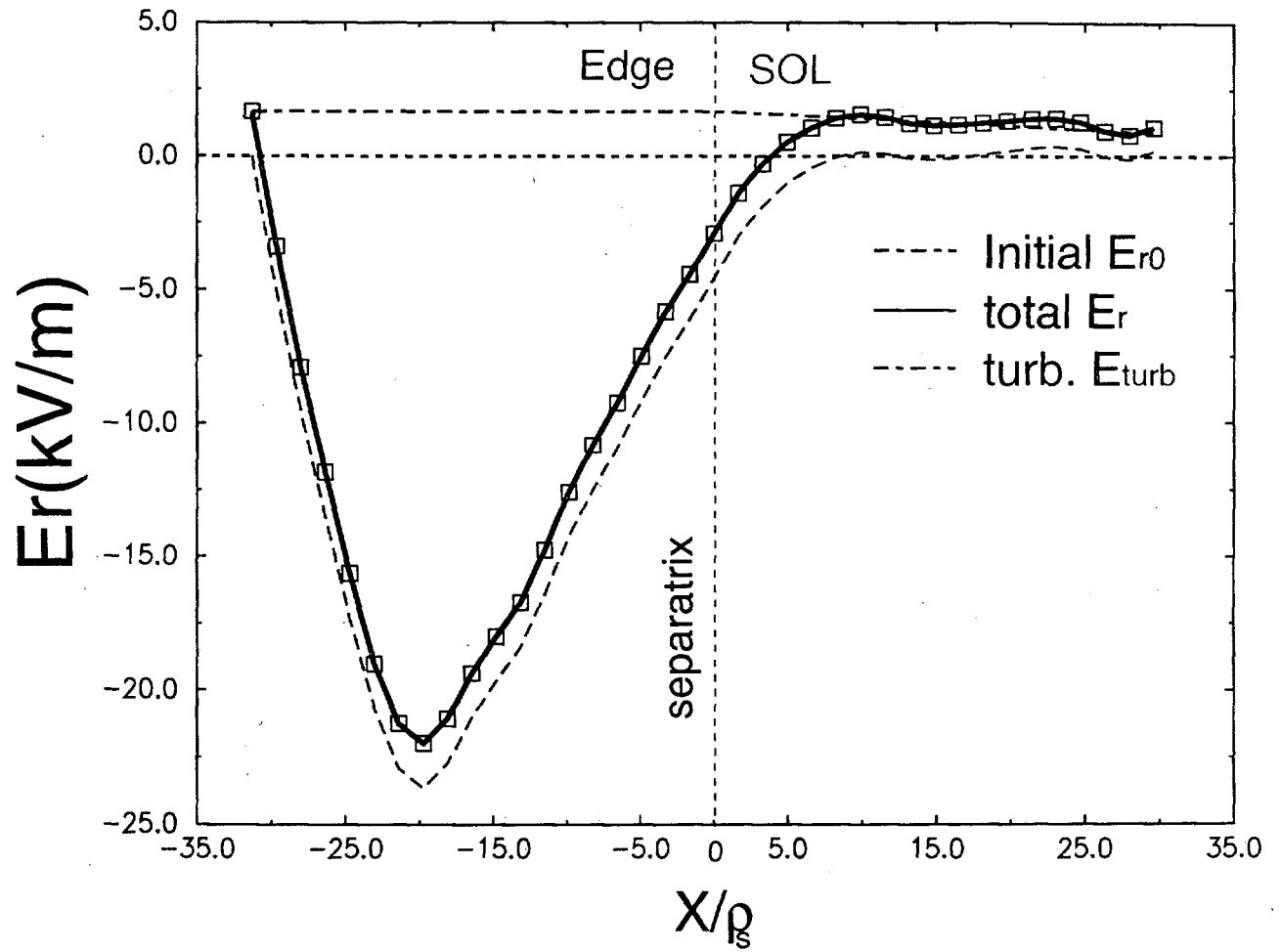


Figure 4: The radial profile of turbulence-generated electric field E_r . The total radial electric field is $E_r = E_{r0} + E_{turb}$.

III. Summary and Outlook

We have presented a model for 3D boundary turbulence in tokamaks which evolves radial electric field together with turbulence. Preliminary encouraging results have been obtained when comparing with probe measurements. We find that in a typical Ohmic discharge, SOL instabilities dominate boundary plasma fluctuations in HT-7 tokamaks due to the flow-shear suppression of turbulence inside the separatrix. The systematic benchmark and validation with experiments are necessary to obtain a realistic simulation tool for experimental data analysis on a routine basis.

We propose to establish the Virtual Center for boundary plasma turbulence, a collaboration between computationalists, theorists, and experimentalists in China which will build on the current generation of boundary plasma turbulence code (BOUT). The center will develop stronger collaborative relations with the US BOUT modeling efforts. BOUT will be used to uncover the basic physical mechanisms of important edge phenomena and to predict edge plasma behavior for evaluation and optimization of future devices. The code will be applied to key issues including the role of non-diffusive and/or large-event-dominated transport, the transition to the enhanced high-confinement mode, edge-localized modes, core density-limit phenomena, and characterization of the loss and fueling channels through the edge plasma. Developing the Virtual Center would also contribute to efforts to bring the bright graduate students to the fusion programs

IV. ACKNOWLEDGMENTS

We are pleased to acknowledge useful conversations with Drs. K. H. Burrell, R. H. Cohen, M. Greenwald, W. M. Nevins, M. Porkolab, T. D. Rognlien, D. D. Ryutov, A. J. Wootton, and S. Zweben. The simulations were done on the NERSC T3E and IBM SP.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

References

- ¹Xu, X.Q., and Cohen R. H., Contributions to Plasma Physics , **38**, (1998) no. 1-2, 158.
- ²Xu, X.Q., et al, Phys. of Plasmas, Vol.7, 1951 (2000).
- ³Xu, X. Q., *et. al.*, in Plasma Physics and Controlled Nuclear Fusion Research, Proc. 17th Int. Conf. Yokohama, Japan (IAEA, Vienna, 1998), IAEA-F1-CN-69/TH4/04.
- ⁴Myra, J. R., D'Ippolito, D. A., Xu, X. Q., and Cohen, R. H., Physics of Plasma , Vol. 7, 4622(2000).
- ⁵Xu, X. Q., *et. al.*, in Plasma Physics and Controlled Nuclear Fusion Research, Proc. 18th Int. Conf. Sorrento, 2000, IAEA-F1-CN-69/THP2/03.
- ⁶Mazurenko, A., Porkolab, M., Xu, X. Q., Nevins, W. M., *A Study of Quasicoherent Fluctuations in High Confinement Mode of Operation of a Tokamak Plasma*, submitted to Physics of Review Letter, 2001.
- ⁷Wan, B. N., *et. al.*, in Plasma Physics and Controlled Nuclear Fusion Research, Proc. 18th Int. Conf. Sorrento, 2000, IAEA-CN-77/EXP5/11.

University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551

